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The effects of clear-felling established forestry on stream-flow losses from the Hore sub-catchment

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Abstract

The effects on streamflow of clear-felling a substantial part of the established forestry within the Hore sub-catchment at Plynlimon were estimated by a regression comparison of pre- and post-felling rainfall/runoff relationships and by a model based on evapotranspiration estimates from plot studies of established forestry and heather moorland. Increases in streamflow were predicted using both methods, with those using the regression method being substantially larger than those using the model. The largest increases using the regression method occurred about 5 years after the end of felling, and amounted to 10.5% of the measured annual flow.

On a seasonal basis, the largest increases using the regression method occurred during the latter half of the year, whilst the model predicted the largest increases during the summer months. These patterns are explained in terms of forest transpiration and canopy interception.

Introduction

Many of the forested areas in the Hafren forest at Plynlimon are well within the felling age, typically 40–60 years, for coniferous forestry in upland areas of the UK. In 1985, the Forestry Commission initiated a programme of felling within the Hafren. Most of this took place in the Hore sub-catchment, and involved the felling of Norway and Sitka spruce planted in 1937/38 and 1948 to 1950.

Past studies reported in the literature have described detrimental effects on streamflow from clear-felled catchments. These include increases in streamflow (Bosch and Hewlett, 1982), nutrient losses (Likens *et al.*, 1970) and sediment losses (Packer, 1965). Such effects, should they occur in the Plynlimon area, are of particular concern, as runoff from the Hafren, and other forested areas, drains directly into Llyn Clywedog, a river regulation reservoir.

This paper describes a study of the effects of the clear-felling on streamflow from the Hore. It complements past studies on nutrient (Durand *et al.*, 1994) and sediment losses (Leeks, 1992).

Study area

A detailed description of the land use, soils, and geology of the Severn catchment has been given in Newson (1976), and the hydrological instrumentation and results up to 1985, immediately prior to the felling, are given in Kirby

et al., 1991. Long term (1975–1984) average annual rainfall to the Hore is 2514 mm; of this, 1850 mm became streamflow.

The felling in the Hore began in the summer of 1985 and continued for approximately four years. The timing and extent of the felling was determined by digitizing a map of the felling schedule supplied by the Forestry Commission (Fig. 1). This produced the timetable shown in Table 1.

This timetable shows that, during the four year felling period, an area of 90.8 ha, or 28.9% of the catchment area, was affected. This figure was confirmed by the analysis of two Landsat images of the area, one recorded on the 27th September 1985, and the other on the 6th September 1989. This analysis showed that 88.2 ha has been felled within the Hore (Roberts *et al.*, 1994).

The Forestry Commission Schedule (Fig. 1 and Table 1) shows that some felling occurred prior to 1985. This occurred mainly in 1981 and 1982 and involved unproductive areas affected by windthrow in the upper reaches of the sub-catchment. It would be expected that the felling of these unproductive areas would have a minimal effect on streamflow compared with the felling of the larger, more productive forestry areas in the lower reaches of the sub-catchment. Most of the felling in these areas occurred in 1985 and 1986 (Table 1). Whole-tree harvesting was not employed, and a great deal of brash was left on the ground

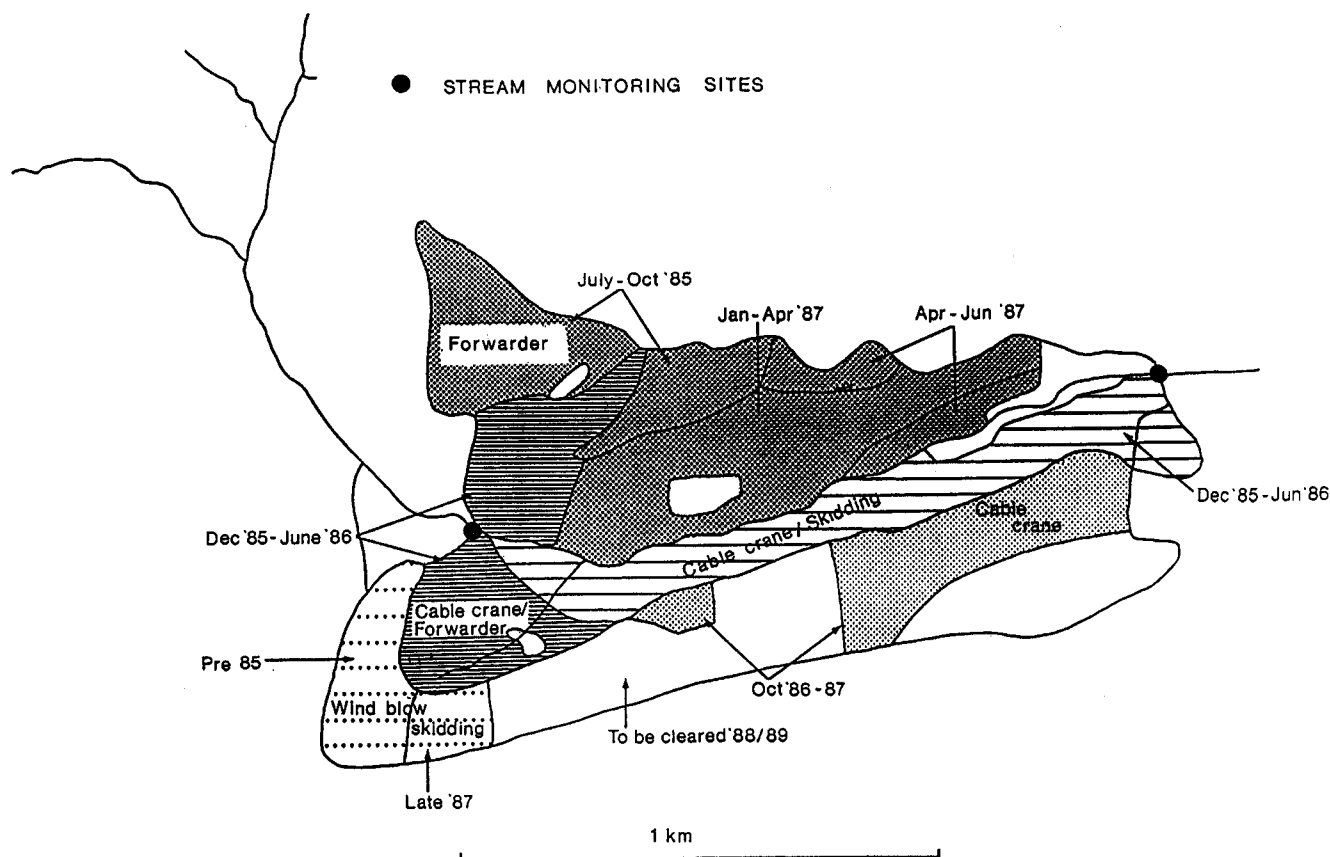


Fig. 1. Schedule of felling in the Hore sub-catchment.

surface. This would normally be allowed to rot for about 2 years before re-planting. If necessary, a herbicide would be applied to suppress weed growth.

Method

The main method used to estimate the effects of the felling on streamflow was a comparison of pre- and post-felling rainfall/runoff relationships for the Hore. This was prefer-

Table 1. Timing and extent of the felling in the Hore.

Period	Area felled (ha)	Percentage of catchment
Pre-1985	5.6	1.8
July → Oct 1985	13.1	4.2
Dec 1985 → June 1986	31.7	10.1
Oct → Dec 1986	11.7	3.7
Jan → April 1987	15.7	5.0
April → June 1987	4.1	1.3
Late 1987	2.3	0.7
1988/89	12.2	3.9
TOTAL 1985–1989	90.8	28.9

able to a comparison between streamflow from the Hore and that from a 'control' catchment because Landsat images showed that significant areas of the other forested sub-catchments were also felled between 1985 and 1989; this would limit the usefulness of these sub-catchments as controls. The use of one of the grassland sub-catchments as a control was rejected because evaporation and, hence, streamflow losses from forested and grassland areas is subject to different controls, and is affected by factors other than the felling.

The available data record, 1975 to 1995, is conducive to a 'before and after' approach, with the years 1975 to 1984 providing the control, and 1985 to 1995 providing estimates of the effect of the felling.

In addition, a process approach has been adopted to predict streamflow changes as a result of the felling. This involves the use of evaporation estimates from small plot studies under established forest, and heather moorland. Inherent in this approach is the assumption that, when an area of forest is felled, the evaporation losses from that area will change. Following Hall and Harding (1993), it is further assumed that the brash left on the ground will intercept rainfall but that no transpiration will occur. This change in evaporation will be reflected in the streamflow, the actual amount dependant on the areal extent of felling during the period under consideration.

Evaporative losses from forested areas occur as a result of two processes; rainfall interception by the forest canopy and subsequent evaporation, and forest transpiration. Both processes have been studied using a 'natural' lysimeter within the 1937/38 plantation in the lower Hore (Calder, 1976).

Interception was found to be related to precipitation by an equation of the form:-

$$\text{INT} = \gamma [1 - \exp(-\delta \cdot P)]$$

where

INT = interception (mm/day)

P = rainfall (mm/day)

For the Hore during 1974 to 1976, it was found that interception losses could best be estimated using $\gamma = 6.1$ mm and $\delta = 0.099 \text{ mm}^{-1}$. The use of these parameter values results in a long term interception ratio of 0.30.

Transpiration was found to be related to potential evaporation (Penman, 1948) and rainfall by an equation of the form:-

$$\text{TRANS} = \beta \cdot E_T (1-w)$$

where

TRANS = transpiration (mm/day)

E_T = potential evaporation from short grass (mm/day)

For the Hore, it was found that:-

$$\beta = 0.90$$

$$w = 0.045P \text{ for } P < 22 \text{ mm}$$

$$= 1 \text{ for } P \geq 22 \text{ mm}$$

where

P = rainfall (mm/day)

Interception by the forest brash is assumed to be similar to that by 'medium height' vegetation, in this case heather (Hall and Harding, 1993)

$$\text{INT} = 2.65 (1 - \exp(-0.36 \cdot P))$$

where INT and P are as defined above

These various formulations have been applied, on a percentage areal basis, in a daily water balance model (Calder *et al.*, 1983).

$$\text{SMD}_{i+1} = \text{SMD}_i - P_i + \text{AE}_i$$

where

SMD_i = soil moisture deficit on day i

P_i = rainfall on day i

AE_i = estimated actual evapotranspiration on day i

This was done for each year following the start of felling, using the appropriate forested and clear-felled areas as given in Table 1. It was assumed that the soil moisture deficit at the start of each year was zero and that

if at any time the soil moisture deficit became negative i.e. a surfeit, this surfeit would be converted to streamflow, and the following day's deficit set to zero. Streamflow totals for selected periods would be the sum of the soil moisture surfeits.

Results

(I) ANNUAL TOTALS

Figure 2 is a plot of annual runoff against rainfall for the Hore sub-catchment for the period 1975 to 1995. A least squares regression has been applied to the pre-felling, 1975 to 1984, data. This gives an excellent fit with a correlation coefficient of 0.98. The correlation equation has been used to provide estimates of annual streamflow assuming that no felling had occurred. These, and the measured values, are shown in Table 2.

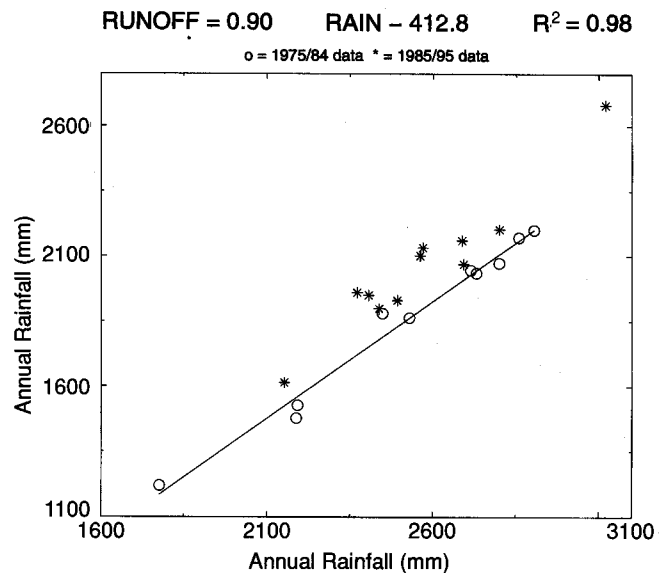


Fig. 2. Regressions of annual runoff against rainfall for the Hore.

Table 2. Post-Felling measured and estimated annual streamflow from the Hore

Year	Measured flow	Regression method Est. flow	Diff	Process method Diff
1985	1899	1780	+119	+21
1986	2203	2107	+96	+80
1987	1950	1753	+197	+126
1988	2161	2005	+156	+133
1989	1930	1830	+100	+158
1990	2070	2010	+60	+155
1991	1961	1721	+240	+148
1992	2134	1899	+235	+165
1993	2102	1892	+210	+152
1994	2681	2395	+286	+165
1995	1615	1525	+90	+143

Measured flows are greater than the estimated flows for all 11 years after the start of felling. The increased flows range from 60 to 286 mm/year, with the largest increases occurring about 5 years after the end of felling.

Also shown in Table 2 are the results obtained from the process based approach. In general, these are lower than the increases in streamflow predicted by the regression method, particularly in the post-felling phase. Possible reasons for this are discussed later.

(II) SEASONAL EFFECTS

Seasonal changes in streamflow as a result of the felling are examined by splitting the year into four three-monthly periods and analysing the changes in the rainfall/runoff relationships for these periods.

Table 3 shows the results of regressing pre-felling period streamflow totals against rainfall totals.

Table 3. Results of regressing pre-felling period streamflow totals against rainfall totals.

Period	Slope	Intercept	R ²
Jan → March	0.80	+39.24	0.91
April → June	0.88	−93.40	0.93
July → Sept	0.99	−231.04	0.84
Oct → Dec	0.90	−92.79	0.98

The regressions have been used to estimate the seasonal changes in flow as a result of the felling. These are shown graphically in Figure 3. Although there is a great deal of inter-annual variability, with some periods of decreased flows, the overwhelming pattern is one of large increases in streamflow during the latter half of the year.

This pattern differs from that obtained using the process based approach (Fig. 4). Here, as expected, the largest increases in streamflow are manifest during the summer months, when the elimination of forest transpiration will be greatest.

Discussion

Bosch and Hewlett (1982), in their review of 60 clear-felling studies, reported maximum annual increases in streamflow during the first five years following felling of 100 mm for a 25% reduction in cover to 400 mm for a 100% reduction i.e. a 40 mm increase in yield for every 10% reduction in cover. Also, Calder and Newson (1979), using results from a 'natural' lysimeter, predicted a 13–21% reduction in percentage runoff, dependent on annual rainfall, following 50% afforestation for a number of major UK upland reservoir catchments. The results obtained using the regression approach, a maximum annual increase of 286 mm or 10.5% in streamflow for a 37% reduction in cover, agree with the predictions of Calder and Newson (1979), but are larger than those given by Bosch and Hewlett (1982). This is probably due to the

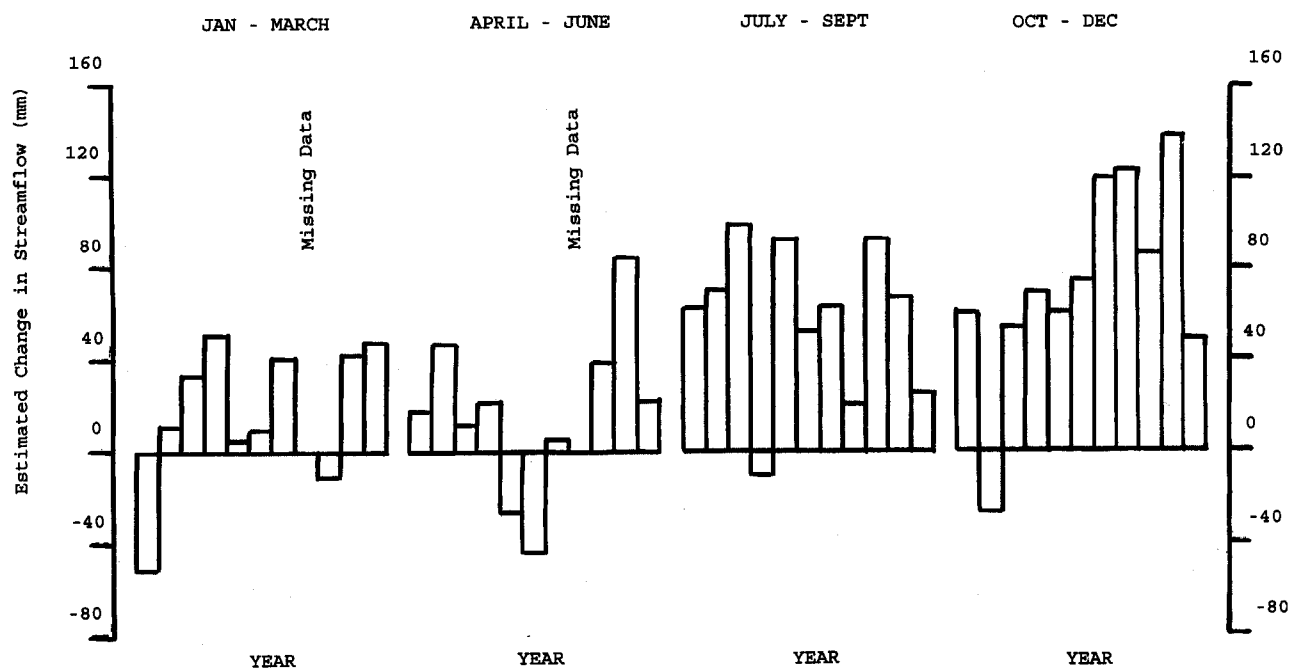


Fig. 3. Seasonal changes in streamflow—estimates using the regression method.

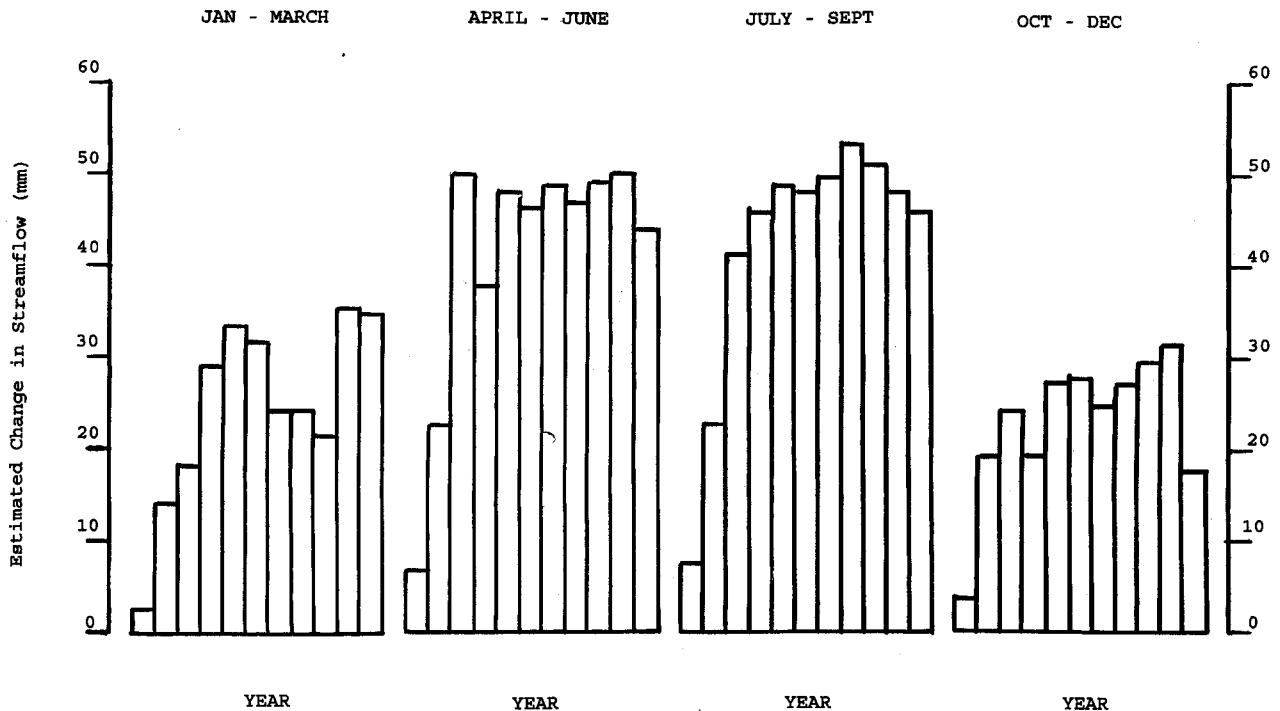


Fig. 4. Seasonal changes in streamflow—model estimates.

higher rainfall, and hence higher canopy interception rates, experienced at Plynlimon compared with the catchments reported by Bosch and Hewlett (1982).

Differences in the results obtained using the two approaches are possibly due to assumptions used in the process based approach. In this, it is assumed that, following felling, the only evaporation would be that of rainfall intercepted by the brash left on the ground. In the absence of data relating to interception rates of brash, it has been further assumed that these are similar to heather moorland, amounting to 19% of rainfall (Calder, 1986). Intuitively, this would seem rather high; a reduction of less than 2% in this interception rate would make the results using the two approaches similar. On the other hand, no allowance has been made for transpiration from emerging vegetation or bare soil evaporation.

The temporal variation in post-felling annual streamflow increases estimated by the regression method (Table 2) shows a reduction on completion of felling in 1989, followed by an increase with a maximum in 1994. This could be as a result of the post-felling practices of allowing the brash to decay for about two years and then removing weed growth by the application of herbicide prior to re-planting. Both practices tend to reduce evaporation losses and hence increase streamflow.

The seasonal variation in the increase in streamflow predicted by the process approach (Fig. 4) is as expected, with the largest increases occurring during the summer months, coincident with the largest reductions in transpiration losses. The seasonal variation predicted by the regression

approach (Fig. 3) is less easy to understand. Possible reasons could include the actual timing of the felling phases, a need to satisfy soil moisture and groundwater deficits (Hudson, 1988), or an increased importance in differences between the interception of rainfall by the forest canopy and brash.

For research purposes, the rate of felling between 1985 and 1989 in the Hore was more rapid than would be associated with normal Forestry Commission practice. This being the case, the predicted increases in streamflow would not constitute a serious downstream problem in a reservoir catchment. Perhaps of more importance would be the increased rates of nutrient (Durand, 1994) and sediment (Leeks, 1992) losses. Of particular importance is the release of phosphorus normally lacking in upland areas. Increases in phosphate concentrations may stimulate algal blooms which utilize oxygen when they decay and lead to anoxic conditions with problems of smell and discolouration in water supply reservoirs.

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